Particle acceleration and non-thermal emission in a nova

The 2010 outburst of V407 Cygni

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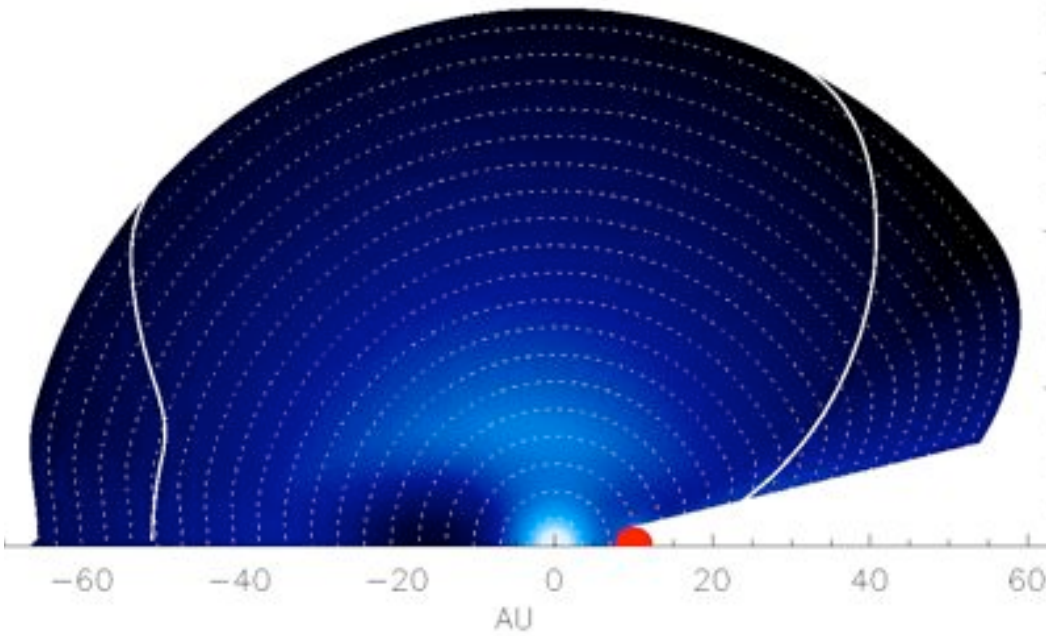
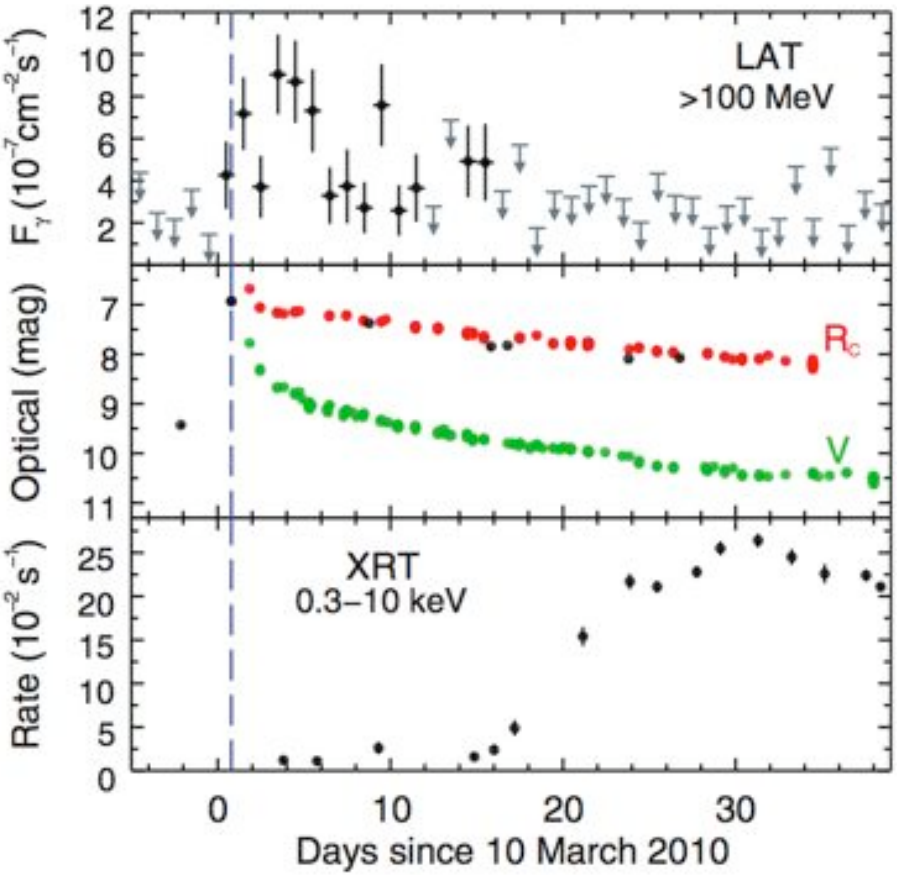


Work submitted to A&A
(arXiv:1209.0625)

V407 Cygni: Introduction

The binary system

- White dwarf (WD) + red giant (RG)
- Period ~50yr, separation ~10AU
- Distance 2.7kpc
- Accretion via wind



The March 2010 outburst

- V magnitude jump by 5 on March 10th
- He/N nova expanding in RG wind
- M_{ej} ~10^{-6} $M_\odot$ and V_{ej} ~3000 km.s^{-1}
- First observed in GeV gamma-rays (by Fermi/LAT)
- Follow-up over weeks/months in radio / X-rays / optical / IR

Transient high-energy emission attesting to short-lived episode of particle acceleration ?

Scaled-down / fast-forward version of supernova ?

Novel test bed for theory on Galactic cosmic rays (GCRs) ?

V407 Cygni: shock dynamics and environment

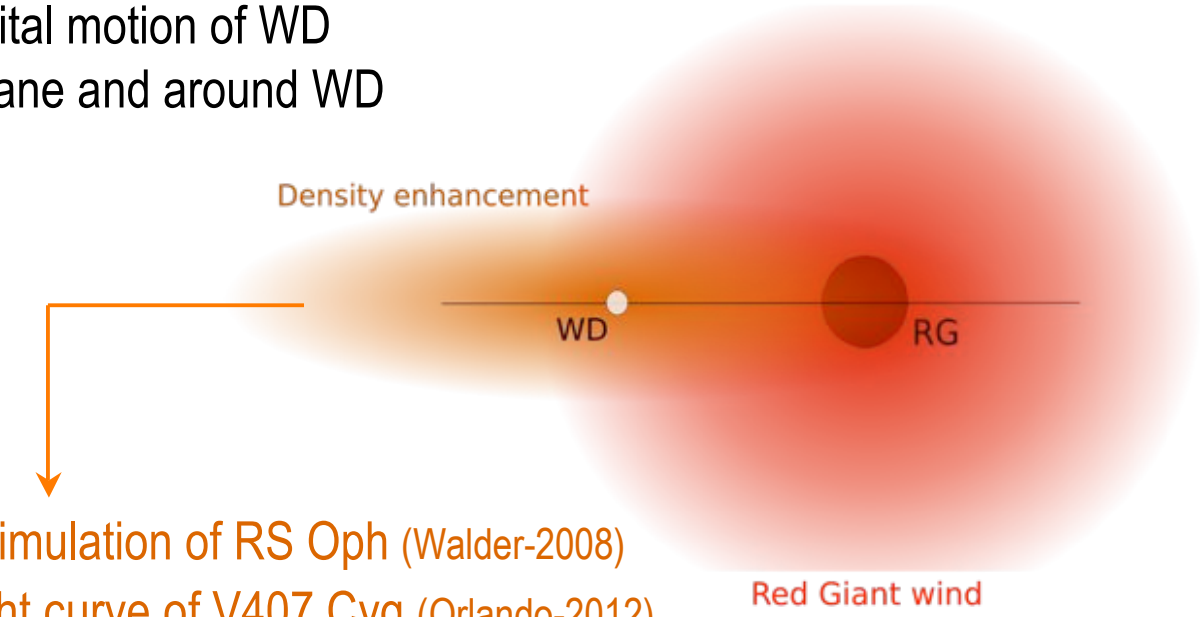
Shock dynamics

- Ejecta-dominated stage : V_{ej}=constant
- Sedov-Taylor stage : $V_{ej}=(2E_{ej}/M_{su})^{1/2}$
- (*Unaccounted: crash into RG and zone behind RG)*

2D cylindrical geometry
azimuthally-symmetric shock elements

Circumstellar density enhancement (CDE) ?

- Accretion from RG wind and orbital motion of WD
- Accumulation of gas in orbital plane and around WD



Suggested by hydrodynamical simulation of RS Oph (Walder-2008)
Required in modelling of X-ray light curve of V407 Cyg (Orlando-2012)

V407 Cygni: The accelerator

Thin-shell approximation

- Acceleration zone and cooling zone
- Particles accumulate behind shock front

Injection

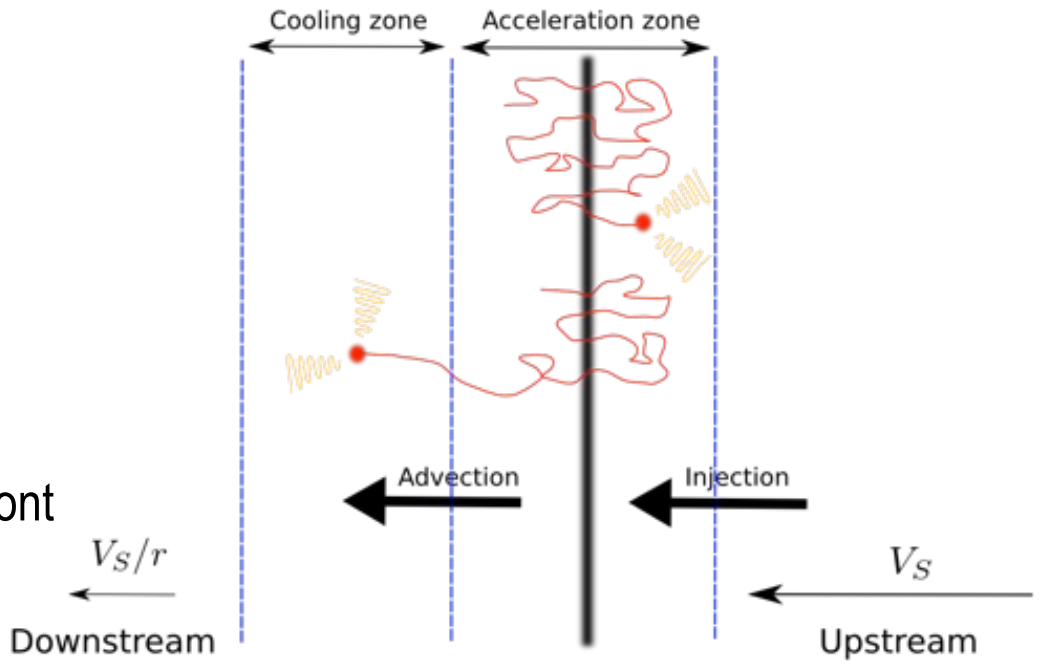
- Scalable fraction of inflowing particles
- Fixed injection momentum over shock front

Acceleration

- Test particle approximation
- Scalable diffusion efficiency w.r.t. Bohm
- Equipartition magnetic field upstream

Losses

- Protons: adiabatic
- Electrons: inverse-Compton
- (others negligible)



Implies power-law distribution with index -2.0
(in the absence of losses)

V407 Cygni: The problem summarized

What do we want to get ?

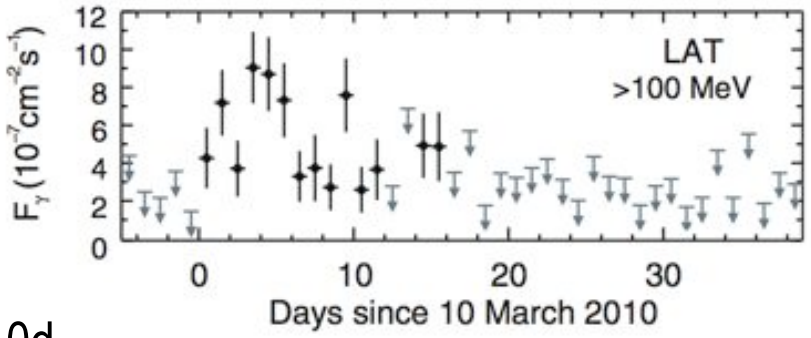
- γ-ray emission maximum within 4d
- γ-ray emission drop by >10 after 20d
- γ-ray spectrum as observed over 0-15d
- Thermal X-rays in 0.3-10keV ~10^{34} erg/s over 20-40d

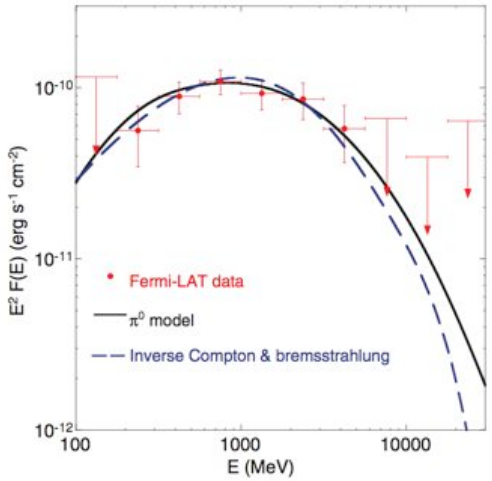
Under what constraints ?

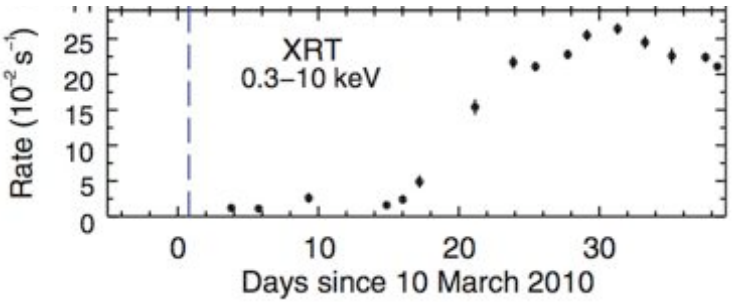
- Non-thermal efficiency ~10%
- e-to-p ratio at injection $K_{ep} = \eta_e/\eta_p$ <1 (~0.01 ?)

What can we tune ?

- Orbital separation R_{orb}~10-15 AU
- Mass-loss rate M_{dot}~10^{-7} $M_\odot$/yr
- Density enhancement
- Ejecta mass M_{ej} ~10^{-6} $M_\odot$
- Injection fractions η_p/η_e, diffusion efficiency ξ







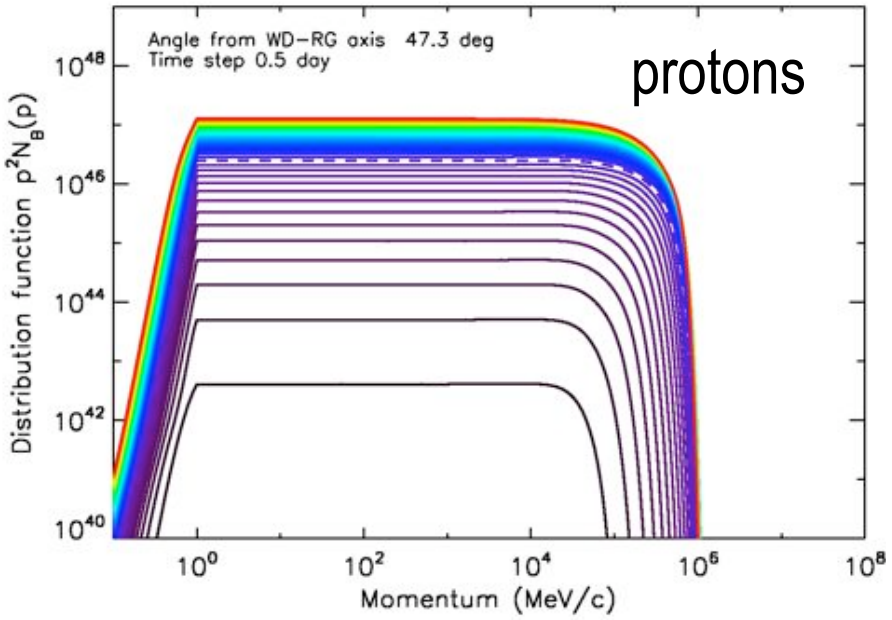
V407 Cygni: non-thermal particles

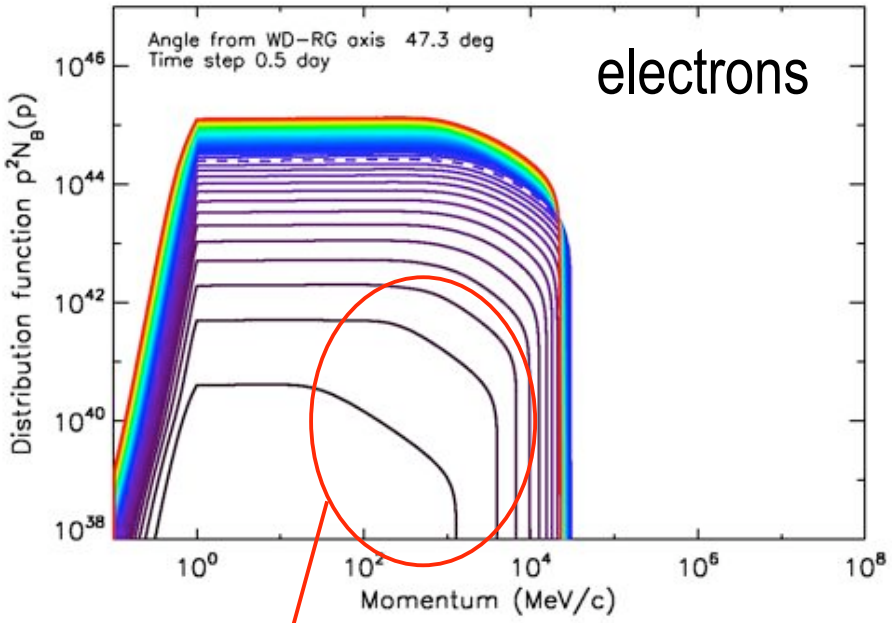
Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-7} $M_\odot$/yr
- M_{ej}=10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 10^{-3}, η_e= 10^{-5}
- ξ=1

Typical momentum distributions $p^2 N(p)$

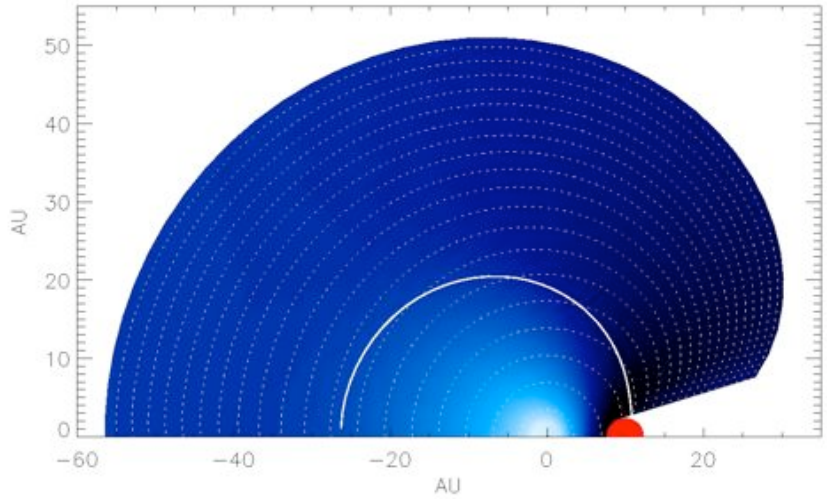
- Protons - age-limited - maximum a few 100GeV
- Electrons - IC-limited - maximum a few 10GeV

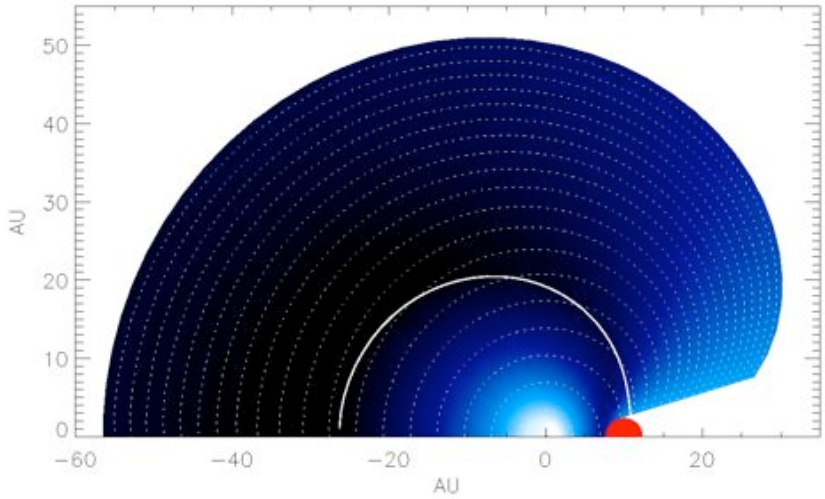




Acceleration limited by IC on nova
Steepening -2 → -3 due to IC

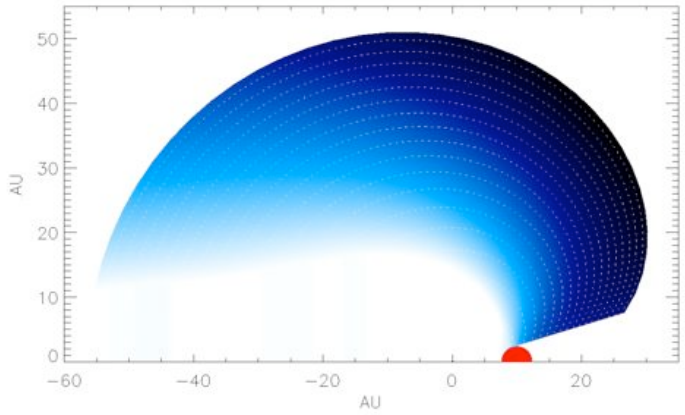
V407 Cygni: non-thermal particles





Particle spatial distributions

- Proton/electron do not reach maxima over same domain
- Non-thermal energy set by amount of swept-up mass

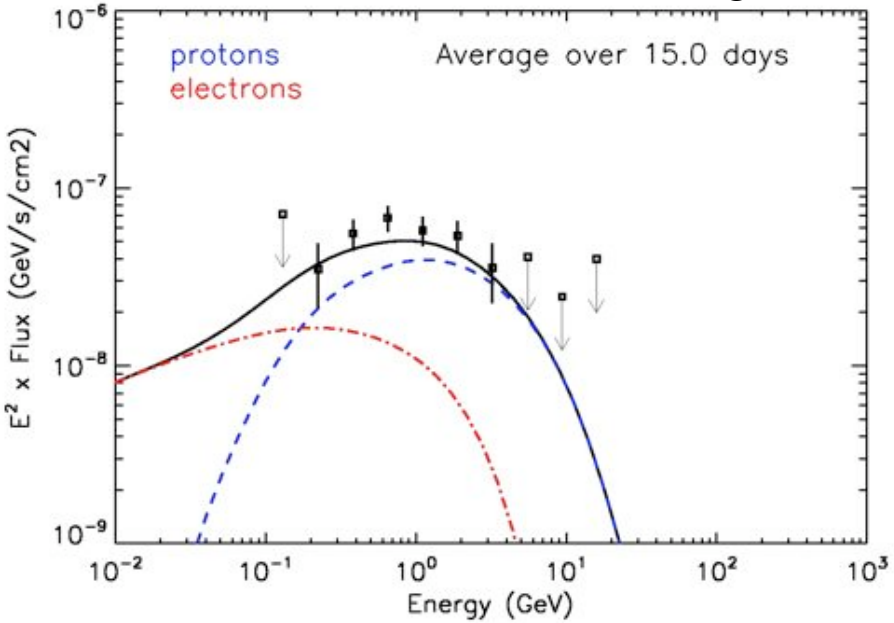


V407 Cygni: Gamma-ray emission

Parameters
- R_{orb}=10 AU
- $M_{ej}=10^{-6}\ M_\odot$
- V_{ej}=3000 km/s

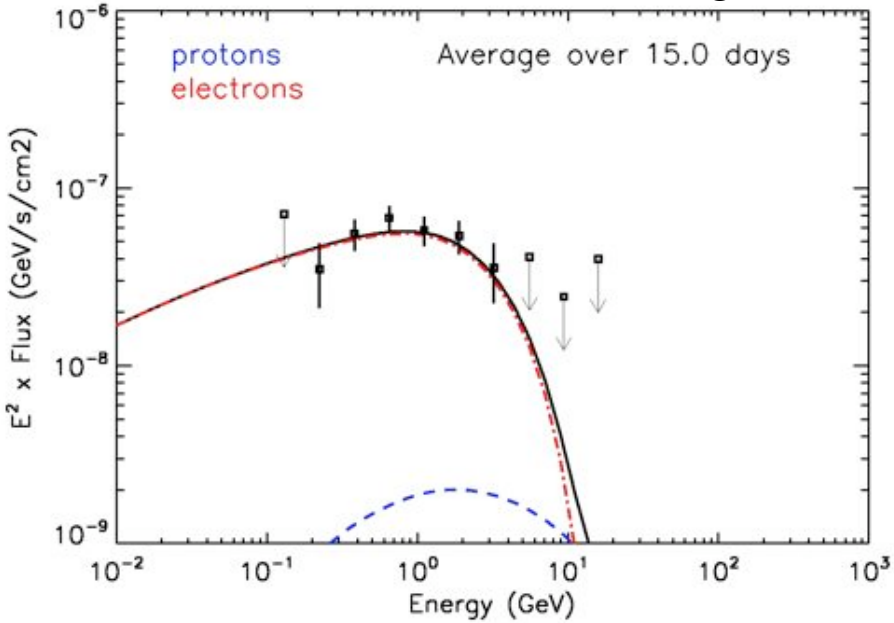
What thermal X-ray constraints imply…

RG mass-loss = $5.10^{-7}\ M_\odot$/yr



Good spectral fit with K_{ep}=1%
Dominantly hadronic emission
BUT: too much thermal emission !

$10^{-7}\ M_\odot$/yr



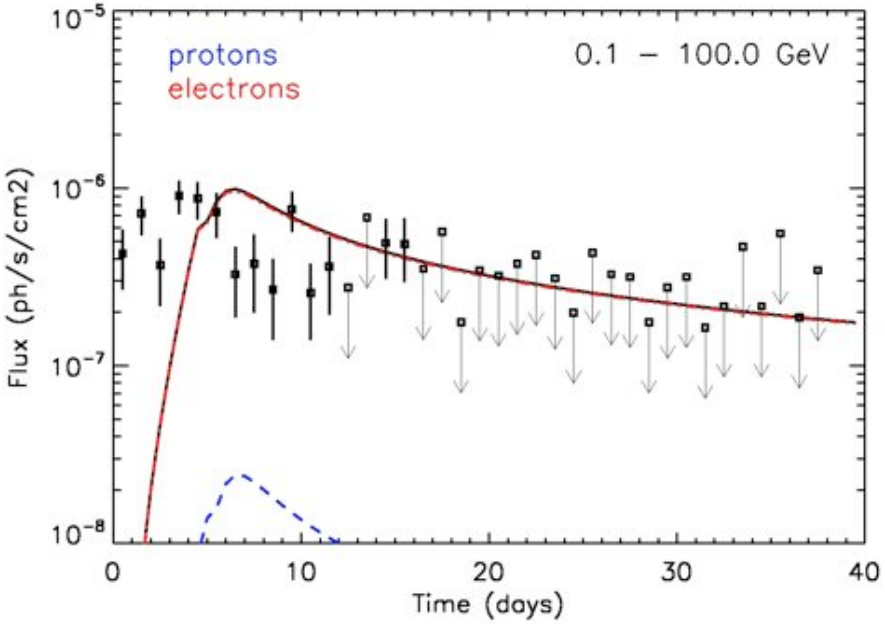
Lower circumbinary densities
Reduced proton radiative efficiency
Proton injection limited by energy budget
Dominantly leptonic emission with K_{ep}> 1%

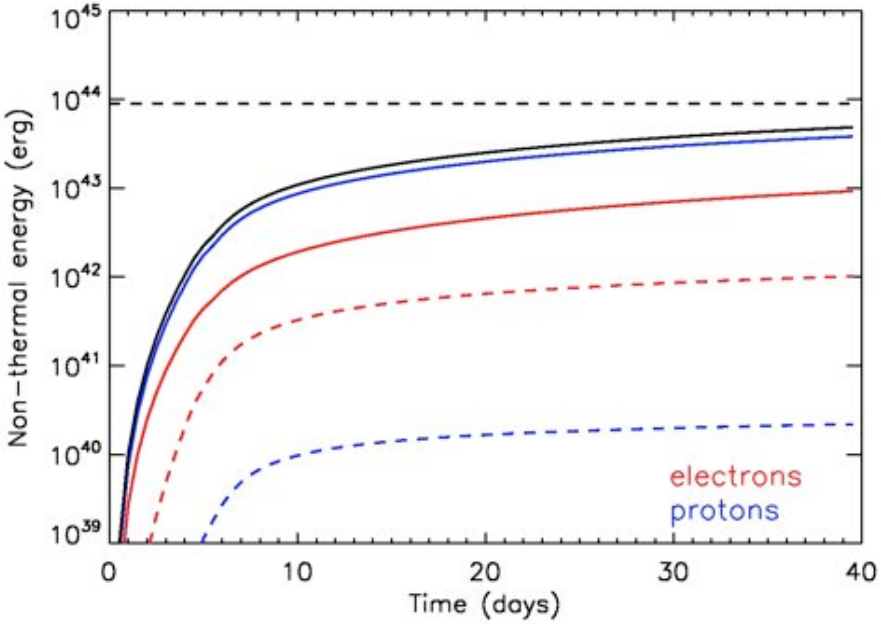
V407 Cygni: Gamma-ray emission

Parameters

- R_{orb}=10 AU
- Mdot=10^{-7} $M_\odot$/yr
- M_{ej}=10^{-7} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 6.10^{-3}, η_e= 6.10^{-4}
- ξ=3

Why a simple wind environment does not fit…





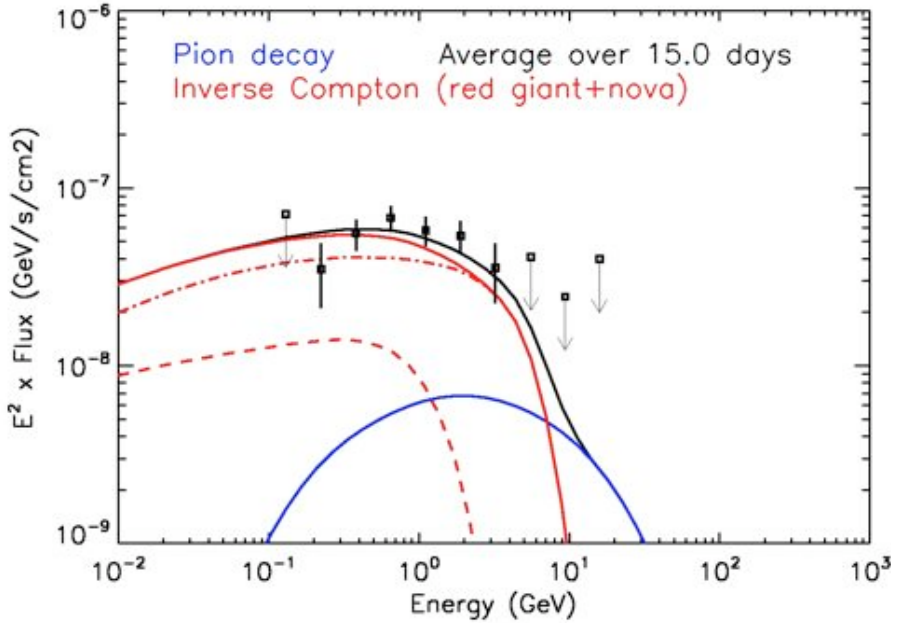
Issue 1: Slow emission rise (would need small orbital separation)
Issue 2: Shallow emission drop (robust whatever the parameters)
Issue 3: Excessive non-thermal efficiency at late times

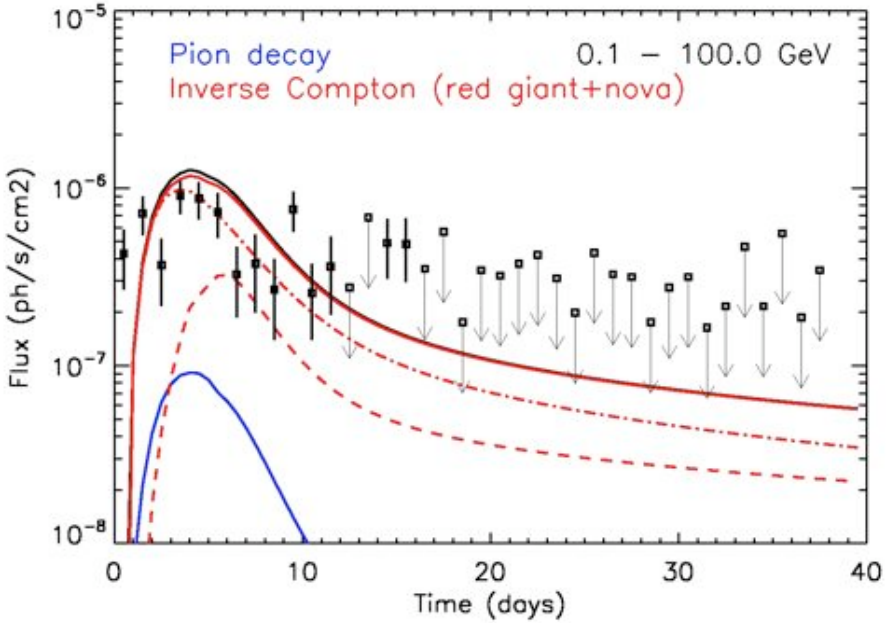
V407 Cygni: Gamma-ray emission

Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-8} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 5.10^{-3}, η_e= 3.10^{-4}
- ξ=3
- CDE 10^8 cm^{-3} / 10AU

How matter accumulation around the WD helps…





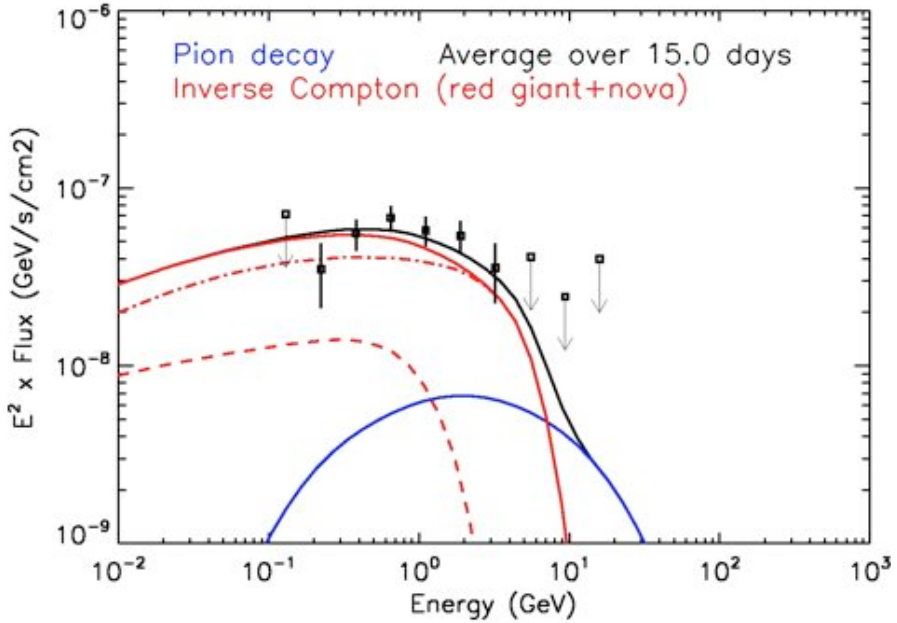
Large reservoir of particles early on, close to nova photosphere
Acceleration drops when shock exits the structure
Bohm diffusion in upstream equipartition magnetic field

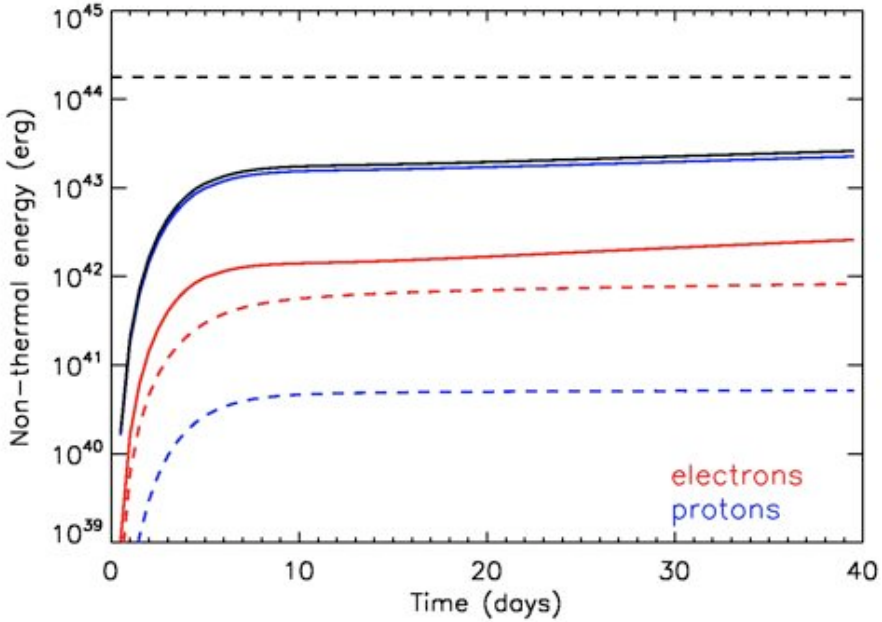
V407 Cygni: Gamma-ray emission

Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-8} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- η_p= 5.10^{-3}, η_e= 3.10^{-4}
- ξ=3
- CDE 10^8 cm^{-3} / 10AU

How matter accumulation around the WD helps…





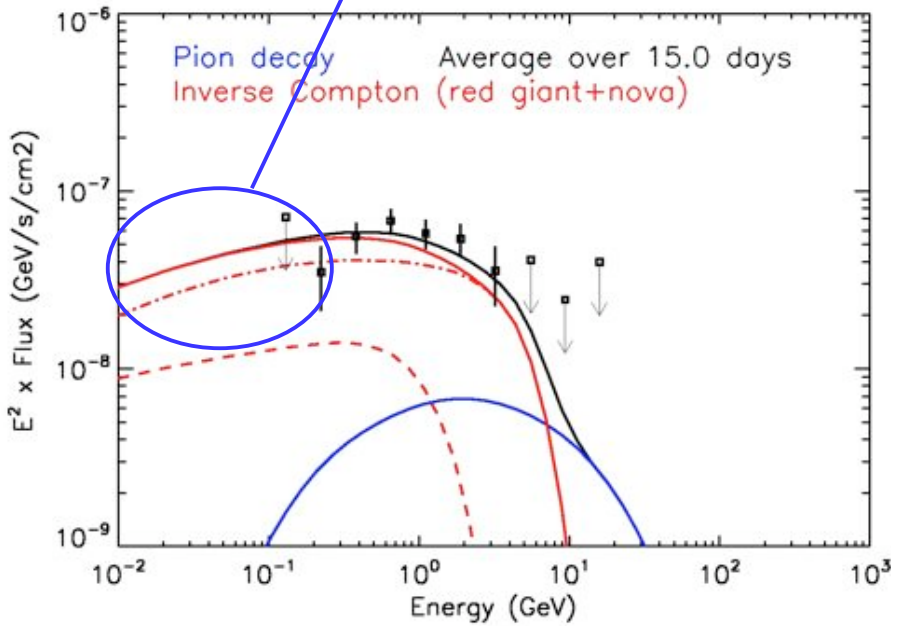
Large reservoir of particles early on, close to nova photosphere
Acceleration drops when shock exits the structure
Bohm diffusion in upstream equipartition magnetic field
Non-thermal efficiency ~10% at day 14

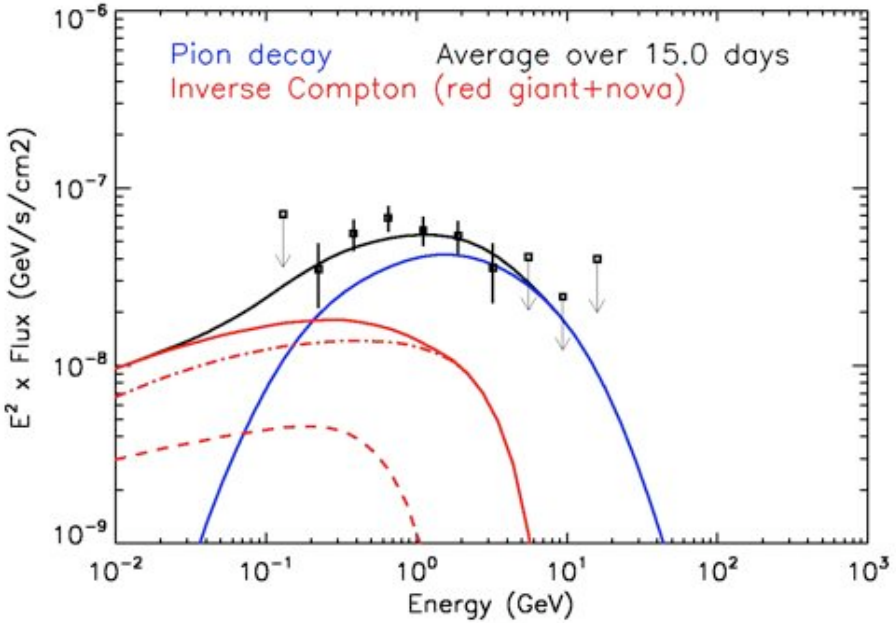
V407 Cygni: Gamma-ray emission

Parameters

- R_{orb}=10 AU
- Mdot=5.10^{-8} $M_\odot$/yr
- M_{ej}=2.10^{-6} $M_\odot$
- V_{ej}=3000 km/s
- CDE 10^8 cm^{-3} / 10AU

Importance of low-energy points <100MeV !





Mixed or dominantly hadronic emission

Large non-thermal efficiency

Cosmic-ray dominated shock

Conclusions/Perspectives

Non-thermal particles

- p → 300GeV, e → 20GeV
- e/p at injection 6%
- 10^{43} erg of particles
- Bohm diffusion in equipartition field

Importance of combined p+e model and multi-λ X/γ/radio constraints

Gamma-ray emission

- Inverse-Compton in nova light if low non-thermal efficiency
- Crucial <100MeV constraints: cosmic-ray-dominated shock ?

About radio constraints

- Synchrotron radiation is absorbed
- Radio signal is free-free emission of UV-ionized wind (Chomiuk-2012)

Conclusions/Perspectives

Getting even more interesting…

- Nova Mon 2012 and Nova Sco 2012
- Classical novae
- Nova envelope ejected at 2000-2500km/s
- γ-ray/optical maxima ~contemporaneous
- ~3-5kpc so more luminous than V407 Cyg

Open questions

- Progenitors with low-density environment: mass reservoir for acceleration ?
- Efficient acceleration over days/weeks: magnetic field strength ?
- Massive circumbinary disks ? Shock convergence behind companion ?

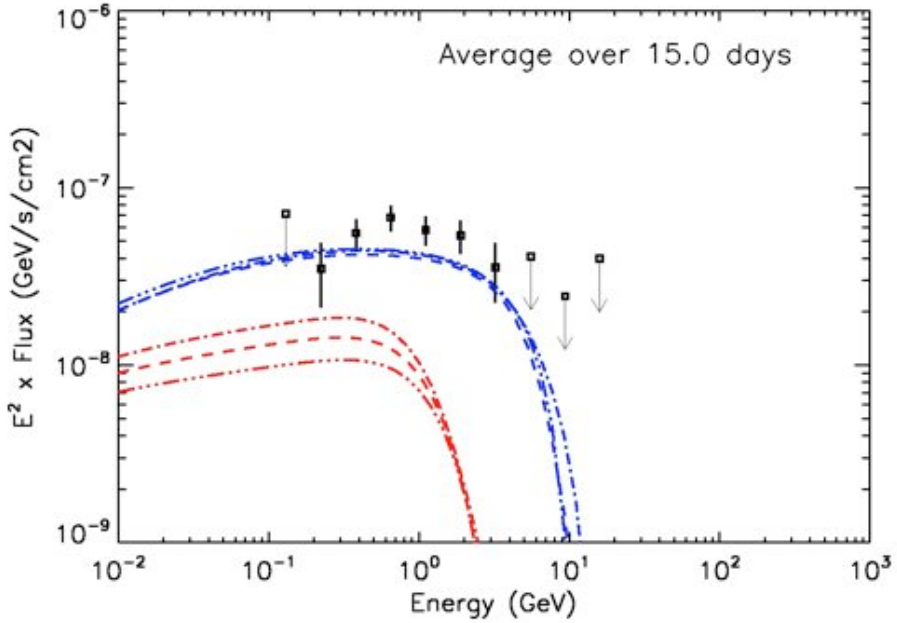
Hopefully more to be learned with future Fermi/LAT detections of novae !

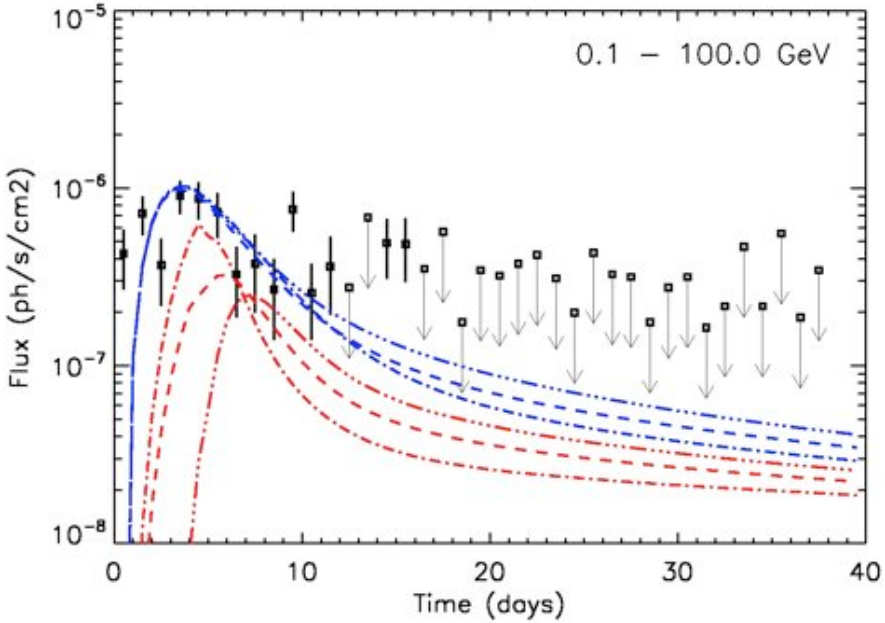
Extra slides

V407 Cygni: Anisotropic inverse-Compton

Effect on spectrum and light curve

- Extreme cases of superior and inferior conjunction, edge-on binary
- Isotropic case for comparison





Conclusions

- Nova IC: not much effect (as expected)
- Red giant IC: superior conjunction favours quicker emission rise and decline
- From emission line analysis, we may be close to superior conjunction (WD behind RG)